Design and installation of a geotechnical monitoring system for monitoring freeze-thaw cycles on a railway track

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ABSTRACT:
Climate change might increase the frequency of events such as heat waves, freeze-thaw cycles (FTC), and flooding and more specifically in permafrost rich regions. These climate hazards are expected to have an impact on railway track performance. There is little publicly available data on their quantitative impacts on railway operations. Such quantitative data is essential for determining when, where and to what extent climate adaptation measures are needed. Freeze and thaw cycle results in frost heave and thaw softening in track foundation (substructure). Both frost heave and thaw softening may lead to unsafe operating conditions especially for rail transit and passenger rail systems as their high operating speed makes them much less tolerant to deviations in track geometry parameters. In order to investigate the effects of a freeze-thaw cycles on an active railway, a structural and geotechnical monitoring system was designed and installed on a section of VIA's track in Ontario. The instruments measure various track parameters such as pore water pressure, heave and deformation at different depth within track foundation, track temperature, strain in the rail, and track surface deformation during freeze-thaw cycles. The data logging system relays static data and high speed data that are triggered by train passages. We show that the selection of instruments and design of the data logging system provide relevant geotechnical data in a manner that could be applied to northern regions and introduce recommendations for future installations. Moreover, we discuss the installation methods appropriate for cold climates because some instruments are temperature-sensitive. Since such systems typically need to be self-sufficient special considerations have to be taken to account for the relatively high power requirements of dynamic monitoring. The suggested system is shown to be useful for track monitoring projects in permafrost-rich regions where freeze-thaw cycles are a concern.

KEY WORDS: climate change, freeze thaw cycles, railway track, substructure, instrumentation.

1 INTRODUCTION

Climate change is likely going to increase the prevalence of extreme weather events and increase average temperatures rapidly in Canada (Lemmen et. al, 2008; Warren and Lemmen, 2014). As a direct consequence, the freeze thaw cycle of soils might be affected in ways that are currently not well understood. This could push the permafrost line further north thus exposing new regions to freeze thaw cycles (FTC). Henry (2008) examined the historical weather data for 31 sites in Canada and found that the annual number of FTC experienced increased at each site, which is attributed to the effect of climate change. This new reality will create challenges for the maintenance and operations of railways in Canada. There is currently very little published work that offers quantitative data on how railways are affected. Obtaining this information is a crucial first step in planning future intervention and maintenance of railways.

Freeze and thaw phenomena result in frost heave and thaw softening in track foundation and the supporting soil. The primary mechanism through which frost affects the foundation is the formation of ice lenses from water flowing under capillary action from unfrozen soil into the freezing zone (Takagi 1979, Li et al. 2016). The water that comes upward from the unfrozen soil by capillary action creates ice lenses and increases the volume of the frozen soil. In order for ice lenses to develop, freezing temperature, a source of water and frost-susceptible soil is required. The most frost susceptible soils have low plasticity, fine grains, and yet high rate of hydraulic conductivity such as silt, fine grained sand, and clay with low plasticity to allow the movement of water above the groundwater table due to the capillary action (Sheng et al. 2014). Conversely, thawing of ice lenses can create conditions that could be as damaging as the frost heave. The thaw-softening, also referred to as track softening, happens when the ice lenses start melting from the top downward and the free water is unable to drain from the track because of the frozen and impermeable soil. The high amount of water remaining in the substructure can cause a softening of the soil and result in drastic reduction of track strength and degradation of track geometry. Both frost heave and thaw softening may lead to unsafe operating conditions especially for rail transit and passenger rail systems as their high operating speed makes them much less tolerant to deviations in track geometry parameters than slower rail freight transport.

In order to characterize and measure the effects of FTC on performance of railway track, a section of railway track in eastern Ontario, was blanketed with geotechnical and structural health monitoring instrumentation. This is the first step in a long term project in collaboration with the National Research Council (NRC) to develop proactive monitoring of critical rail sections in northern Canada. In this first phase, both long term static monitoring and dynamic monitoring are conducted with an array of instruments: piezometers, strain gauges, multipoint borehole extensometers (MPBX), ShapeAccelArray chains and thermistor strings.

Piezometers provide direct reading of pore water pressure and dynamic overpressures. The former grants precious information regarding soil saturation during thawing and generally useful geotechnical information. The latter is more commonly required in clay and soft soils where overpressures can disturb the local structure possibly going as far as creating partial liquefaction or differential settling. Other insights of underground behaviours can be gleaned from MPBX. Like piezometers, they are used for static and dynamic monitoring, providing direct information on the heave over long period of time and information on the behaviour of the track foundation during train passages in critical period such as during the spring. This data is complemented with thermistor strings to measure soil temperatures and estimate the position of the freeze line during transitional periods. Additional long term data obtained from ShapeAccelArray attached on both sides of track.

2 MONITORING SYSTEM

2.1 Site overview

The site selected for the structural and geotechnical instrumentation is located in eastern Ontario and is only used for the passenger trains. The track consists of 57 kg/m (115 lb/yd) continuously welded rail on ballasted track and wooden ties. This subdivision is classified as a class 5 track, which is the Transport Canada's highest classification, and carries 160 km/h trains. The site has experienced frost-heave effects in the past and showed rough surface (profile) measurements during the spring time which is an indication of FTC-induced problems.

This section will discuss in detail the selection of each instrument type, their location and the installation methods. Figure 1 shows a not-to-scale schematics of the location and type of each instrument type. Geophones were installed 30 m from each end of the section in order to trigger dynamic data storage only during train passages. On either side of the track, a ShapeAccelArray (labeled SAA) was installed to measure static differential settlement as well as any changes in crosslevel. Between the two rails, boreholes containing piezometers, MPBX and thermistors were drilled. Finally, resistive strain gauges were installed in the middle of the monitored section to provide both static and dynamic data on each train passage.

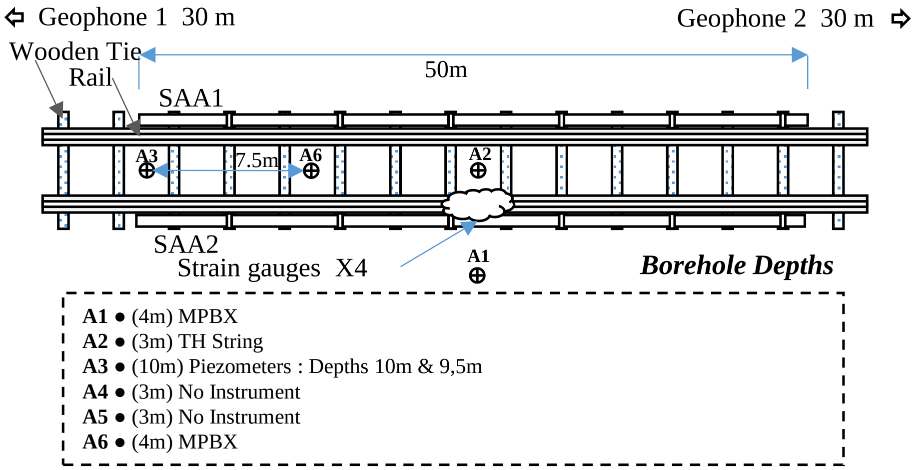

Figure 1 Overview of the instruments installation and locations on the rail section

2.2 Piezometers

The piezometers selected for this project Geokon 3400SV piezometers with a 100 kPa range. In most applications vibrating wire piezometers are recommended. They are robust and durable but have a major drawback for this application; they are not well-suited for dynamic measurements. Without advanced custom hardware, the typical sample rate of a vibrating wire piezometer is approximately 0.5 Hz, far from the sample rate of 100 Hz required to analyze dynamic events caused by train passages (Heirich 2011, Broquetas 2012). Specialized hardware that can extract high speed data from vibrating wire piezometers are available on the market but they are not cost-effective and have important limitations, including a maximal theoretical sample rate lower than 100 Hz if several instruments are read simultaneously. In order to obtain high-frequency measurements, voltage-output semiconductor-based piezometers were installed. They are slightly less stable over long periods of time than vibrating wire piezometers but they can be read at high frequency without significant constraints. Furthermore, with a standard voltage output, it is possible to read them with commonly found high speed data logging and SCADA systems.

The piezometers were installed at depths of 3.7 and 4.3 m. These depths ensure that the piezometers are within the ground water table, protected from freezing and likely to be underwater during FTC. Moreover, they were installed in so-called sand lanterns and separated with bentonite plugs. This prevents water from flowing through the borehole, which could affect the accuracy of the measurements. Special care needs to be taken handle piezometers in arctic weather. The filter assembly should not be left to freeze while saturated with water without specific precautions to prevent ice build-up to damage the piezometer’s diaphragm. Freeze-resistant custom piezometers can be used for these applications.

2.3 MPBX

The MPBX deployed in this project are potentiometer-based SmartMPBX from the manufacturer Mine Design Technology. The potentiometer is the most appropriate method for the specific requirements of this project: vibrating wire extensometers are not compatible with dynamic measurements and linear voltage differential transformers (LVDT) require more electric power than is readily available at the location. The MPBX were installed in boreholes and grouted in place. The grout mix must match the stiffness of the surrounding soil for adequate coupling between the soil and the anchors. A grout that is too soft will not provide adequate coupling and long term stability while a grout that is too stiff will reinforce the soil locally, potentially leading to underestimation of all displacements (Mikkelsen 2002). For loose soil and ballast, it is usually recommended to use “spider” type anchors that have long metal hooks that grip into the soil or surrounding medium.

In this project, the 4 measurement anchors are located at regular interval starting from the surface, potentially yielding detailed information on how each layer (ballast, subballast, subgrade) behaves during train passages during freeze thaw periods. Linear potentiometers can wear out after a certain number of cycles and this study will help establish if they are adequate for future campaigns for long term monitoring when repeatedly submitted to vibration.

2.4 Strain gauges

The strain gauges were Vishay model 250 UW. They were installed on each side of the neutral axis on one rail. The strain gauges are used mostly to monitor thermally induced longitudinal stress in the rail and the changes in rail bending moments caused by the change in track stiffness under during the FTC. Furthermore, they are used to measure each event dynamically and could be used to estimate long term fatigue.

The rail was grinded to a smooth finish and thoroughly cleaned with degreasers. The gauges were glued into place with low-temperature epoxy. The assembly was then covered again in epoxy to protect it from sunlight and impacts. This method is well suited for fast and easy installation as opposed to welding, but special care needs to be taken when handling the bonding epoxy to ensure proper attachment. Even low-temperature rated epoxy will take hours or days to fully harden and the gauge should be fully protected from impact and vibration until curing is complete.

2.5 ShapeAccel Array

ShapeAccel Array or SAAs are chains of micro-electro mechanical sensors (MEMS) accelerometers that are used as inclinometers to measure the tilt of each segment of the chain with respect to gravity. For this application, they were installed over 50 m along the track as a tool to monitor heave or sag in the section of interest. When two are deployed in parallel on each side of the track, changes in the crosslevel can be estimated if one side heaves or sags more than the other.

Moreover, they are used to measure localized heave or sagging over the course of a year and estimate its linear distribution along the track, which can’t be done with single, localized, MPBX. The main challenge in using SAAs in this application is to generate absolute measurements. A known reference has to exist for the instrument to provide absolute data. For instance, if the entire length of the SAAs sinks evenly, this change will not be picked up by the instruments as only changes in inclination are measured. A typical workaround for this is to install SAAs much longer than the anticipated active zone. Other approaches are to regularly survey one end of the SAA or to anchor one end of the SAA to a stable object or building outside the active zone. Because the track runs in a rural area, there was no static structure to attach the SAA to. Surveys are performed manually several times a year as a reference but for future deployments in remote areas, this could be cost-prohibitive or impossible to apply.

SAAs are not perfectly suited for arctic applications as their regular range of measurement temperature goes down to -35 °C. However, since the critical periods are during the freezing and thawing, good quality data will still be available as air temperature should be close to freezing.

2.6 Thermistors

Thermistors are model 3810 by manufacturer Geokon. Thermistors are routinely used in permafrost applications to follow underground soil and water temperatures. In this case, they were used to monitor the response of track to variations in ambient temperature and to follow the depth of the frost line within the grade and subgrade. Special care should be taken when handling thermistors (or any electrical cable) at low temperatures, even for arctic-rated cables. Indeed, the sheath can usually survive slow movements but sharp movements or impacts could damage it more easily than at warm temperatures and lead to water ingress.

3 DATA LOGGING SYSTEM

Due to the harsh winter weather and the winter expected at higher latitudes for future installations, one of the main challenges of this design is that the data acquisition system should perform dynamic measurements, require very little power and work at very low temperatures (-40 °C in this project, and down to -55 °C for future arctic and subarctic projects). There are only a small number of options available on the market that fulfill these requirements such as Campbell Scientific and National Instruments data acquisition systems.

Figure 2 shows the overall structure of the system. For dynamic measurements, Campbell Scientific’s CR6 was used. Though it is not designed specifically for high-speed data acquisition, it is possible to reach the required sample rate. Its maximum program scan rate is 1000 Hz but channel readings are sequential (i.e. it reads each channel one after the other rather than simultaneously). In consequence, the delay induced by each measurement lowers the overall scan rate. Despite this limitation, it was still advantageous to multiply the number of CR6 to achieve the desired sample rate (100 Hz) on all instruments in comparison to the more expensive but more versatile National Instruments data acquisition systems. Static and temperature measurements were conducted with a CR300 while SAA measurements were conducted with a CR800. The entire data acquisition system is connected to remote servers for data visualization and download through a cellular modem chosen for its low power requirements and large range of operating temperatures.

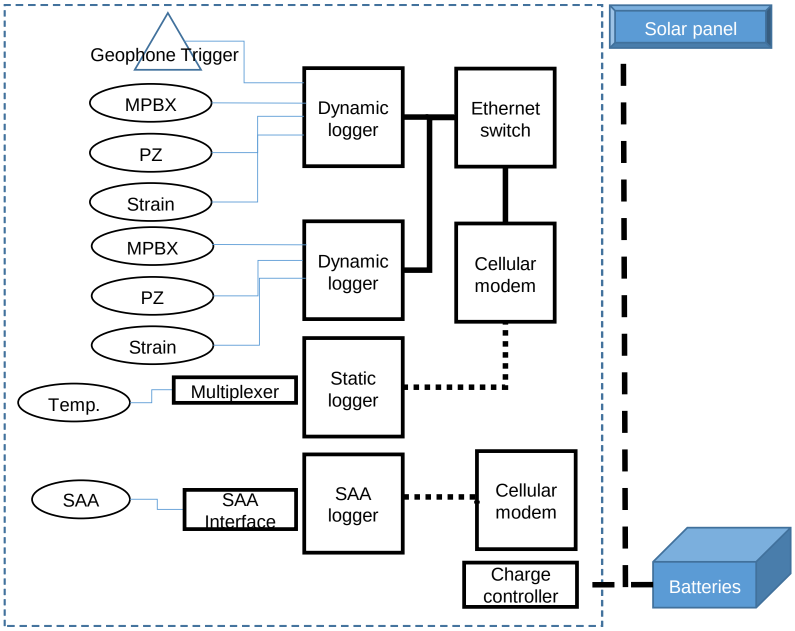

Figure 2 High level overview of the data logging system

Due to the remoteness of the specific section under study, the entire system is solar-powered. While the amount of sunshine in winter is low in Eastern Ontario (< 2.5 hour of sunshine duration per day on average) (Environment Canada), it is higher than in many regions where permafrost is common. Other approaches will have to be devised to further lower power requirements. One such approach would be to lower the acquisition rate as low as possible while attaining the required frequency range for dynamic responses. Another approach is to synchronize burst data with train schedules and leave it on standby between passages. Similarly, turning on the communications module (e.g. cellular modem, satellite modem) for short periods of time can significantly reduce the power requirements. The main concern of only turning on the communication module on demand is that it could hamper real-time data transmission.

4 EXAMPLE MEASUREMENTS

Detailed analysis of the collected structural and geotechnical data is beyond the scope of this work, but a cursory glance is offered here. Figure 3 shows dynamic events as measured by piezometers and strain gauges. The effect of a single train passage can be easily seen as each wheel passes over the sensors for each of which a small dynamic overpressure is registered.

Figure 4 shows dynamic measurements for the in-track MPBX. Only the top anchor appears to be affected significantly by train passages. It is unclear at this time why only one anchor appears to dynamically react to train passages, but it could be linked to the installation method that relied on grouted anchors rather than spider-type anchors.

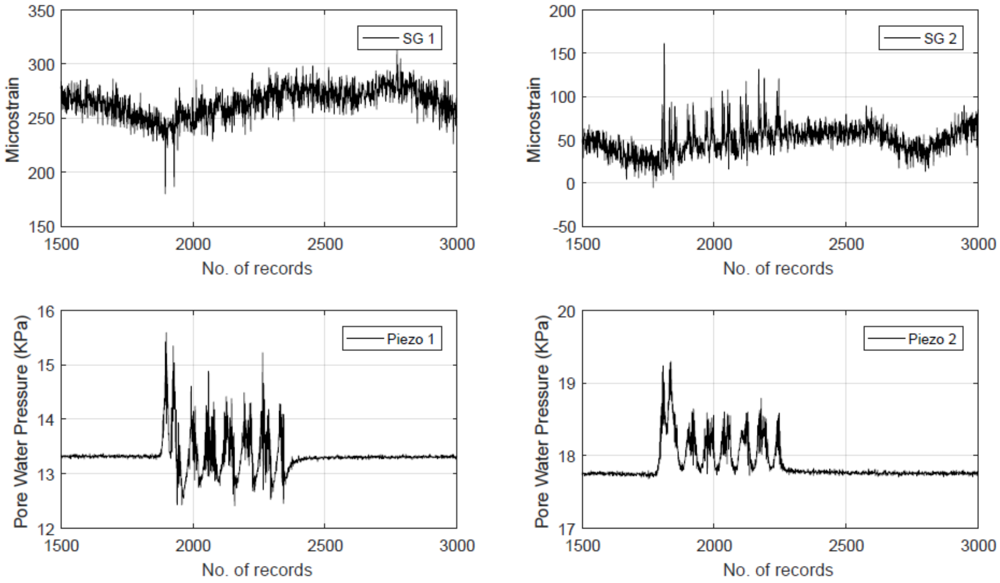

Figure 3 Comparison of several dynamic measurements for a single train passage. The time period displayed is 15 seconds. (a) Some strain measurements show uneven and weak responses; (b) Strain measurement clearly displays the effect of a single train passage; (c) and (d) piezometers showing the effect of train passages with short burst of added pore water pressure.

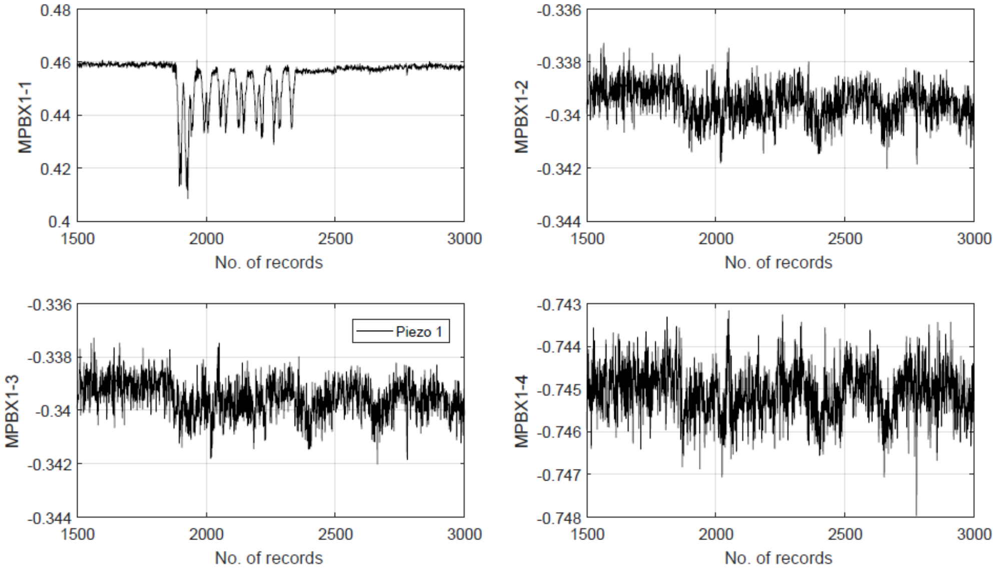

Figure 4 Dynamic measurements as measured by a 4-point MPBX. The top anchor shows significant movement.

5 CONCLUSION

In collaboration with NRC and Via Rail, a geotechnical and structural monitoring system was designed and installed in Eastern Ontario as part of a pilot project. Instruments were chosen and the installation was designed to provide data regarding potential frost heave damage of critical infrastructure. Future expansions of the monitoring project will be in subarctic regions on rail infrastructures where permafrost rich soil becomes more routinely submitted to FTC. Future work will focus on analyzing the long term data and explaining the observed behavior of each instrument. It is likely that the installation procedure of the MPBX will have to be reviewed to better adapt it to installation in ballast and to protect it from excessive vibration. Power requirements will have to be carefully considered to tailor each system to the available sunshine and temperature profile at each specific location.

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REFERENCES

Broquetas A., Comerón, A., Gelonch A., Fuertes, J. Castro, J. A., Felip D., López, M. A., Pulido, J.A., (2012). *Track Detection in Railway Sidings Based on MEMS Gyroscope Sensors*. Sensors 2012, 12, 16228-16249

Environment Canada (2019) "Canadian Climate Normals 1981–2010 Station Data: Ottawa, Ontario". Environment Canada. Retrieved January 2019.

Heirich, O. and Lehner, A., Robertson P., and Strang T. (2011). *Measurement and Analysis of Train Motion and Railway Track Characteristics with Inertial Sensors*. 2011 14th International IEEE Conference on Intelligent Transportation Systems Washington, DC, USA. October 5-7, 2011

Henry, H.A.L. (2008). *Climate change and soil freezing dynamics: historical trends and projected changes*. Climate Change 87:421–434

Lemmen, D.S., Warren, F.J., Lacroix, J., and Bush, E., editors (2008). *From Impacts to Adaption: Canada in a Changing Climate 2007*. Government of Canada, Ottawa, ON, 448p.

Li, D., Hyslip, J., Sussmann, T. and Chrismer, S. (2016). *Railway Geotechnics.* CRC Press, Taylor & Francis Group, Boca Raton, FL.

Mikkelsen, E., (2002) *Cement-Bentonite Grout Backfill for Borehole Instruments* Geotechnical News, December 2002

Sheng, D., Zhang S., Niu, F., Cheng G. (2014). *A potential new frost heave mechanism high speed railway embankments.* Géotechnique, 13, 402.

Takagi, S., (1979). *Segregation Freezing as the Cause of Suction Force for Ice Lens Formation*. Engineering Geology, pp. 93-100.

Warren, F.J. and Lemmen, D.S. (2014): *Synthesis; in Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation, (ed.).* Government of Canada, Ottawa, ON, p. 1-18.